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# Sharing the burden for climate change mitigation in the Canadian federation

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**Abstract**

Dividing the burden for greenhouse gas abatement amongst the provinces has proven challenging in Canada, and is a major factor contributing to Canada's poor historic performance on greenhouse gas abatement. As the country aims to achieve substantial cuts to emissions over the next decade and by mid-century, such burden sharing considerations are likely to be elevated in importance. This paper uses a calibrated multi-region multi-sector computable general equilibrium model to compare a number of archetypal rules for sharing the burden of a joint commitment amongst members for the case of greenhouse gas reductions in Canada. Because of the substantial heterogeneity amongst Canadian provinces, these different burden sharing rules imply significantly different relative abatement effort amongst provinces, and also significantly different welfare implications. When emission permits are allocated on an equal per capita basis, welfare is increased in Ontario, British Columbia, Quebec, and Manitoba, and significantly reduced in Alberta and Saskatchewan. In contrast, when emission permits are allocated based on historic emissions, Alberta and Saskatchewan are made better off, and Ontario, British Columbia, Quebec, and Manitoba are made worse off. We compare these archetypal burden sharing rules to existing provincial emission reduction commitments, and find that none of the

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standard burden sharing rules comes close to existing commitments. We argue that the debate on burden sharing of greenhouse gas abatement in Canada could be objectified if informed by coherent quantitative analysis such as the one presented here.

**Keywords:** climate, burden sharing, computable general equilibrium analysis.

**JEL codes:** C68, Q50.

# 1 Introduction

Significantly reducing greenhouse gas emissions in a federation requires grappling with the difficult issue of how to allocate the burden of emission reductions amongst the entities that make up the federation. Since the costs of deep greenhouse gas emission reduction are potentially large, the stakes involved in the burden allocation process are high. Furthermore, because the allocation process is about 'fairness', and because there is no widely accepted and objective definition of what is fair, the choice of a 'fair' burden sharing scheme is inevitably subjective.

This paper provides the first analysis focused on sharing the burden of climate change mitigation efforts between Canadian provinces of which we are aware.[1] We use a multi-province computable general equilibrium model, and conduct a number of experiments to examine the economic impact of different burden sharing rules. Our results show that alternative choices of burden sharing rules can significantly affect provincial economic well-being. For example, two burden sharing rules that have been widely considered in the international context base emission permit allocation on historic emissions and population, respectively. Because of the substantial heterogeneity in per capita emissions in Canada, these burden sharing rules impose heterogeneous economic impacts on different regions in Canada. When permit allocation is based on population, Quebec, Ontario, British Columbia, and Manitoba, where per capita emissions are low, would be better off than without a climate policy. In contrast, Alberta and Saskatchewan would be significantly worse off. However, if emission permits are based on historic emissions, welfare in Saskatchewan and Alberta would be nearly unchanged compared to when no policy is applied, and Quebec, Ontario, British Columbia, and Manitoba would be worse off. We also conduct a modeling analysis of recent provincial commitments for greenhouse gas reductions, and compare these commitments to the burden sharing rules we propose. We find that none of the burden sharing rules we examine helps to explain the division of effort implicit in provincial emission reduction commitments.

Previous discussions of how to share the burden of greenhouse gas reductions across Canadian provinces have been contentious. In part, we believe this is because they have not been informed

[1]Peters et al. (2010) conducts analysis of the economic effects of different greenhouse gas mitigation policy approaches on regional well-being, but does not focus directly on burden sharing.

by an analysis of alternative philosophical principles for sharing the burden of a joint commitment. Instead, such a discussion has been suppressed in political and public discussion and in lieu the specific positions of provinces have been at the forefront of the discussion. Our belief is that a more principles-based discussion and analysis of alternative ways to divide the burden for greenhouse gas abatement in Canada, such as presented in this paper, would increase the likelihood of an agreement.[2] For example, while coming to an agreement on the greenhouse gas mitigation obligations of individual provinces has been and will continue to be contentious when approached from this as a starting point, we believe that provinces would be significantly more able to come to agreement on high-level principles that could govern the allocation of burden between them. These principles could then be used to conduct the allocation of emission burden in the formulaic manner described in this paper.

This paper builds on an established literature on burden sharing for environmental problems (and particularly climate change), which is well summarized in a recent paper by Kverndokk and Rose (2008). The literature spans a large range, but two strands are especially relevant here. First, several authors identify potential equity principles for environmental burden sharing, based on different philosophical perspectives (Grubb et al., 1992; Rose, 1992; Rose et al., 1998; Cazorla and Toman, 2001; Ringius et al., 1998). These range from rules in which fairness is judged according to the initial allocation of permits, to rules in which fairness is judged according to the outcome that results from the implementation of the emission mitigation scheme, to rules that govern the process for allocating environmental burden. Second, using numerical models, various authors have attempted to implement these rules to determine implications of various burden sharing rules on economic well-being. For example, Rose and Zhang (2004) show how some of these different burden sharing rules impact regional welfare in the United States; they find relatively little difference in regional welfare depending on the allocation rule. Miketa and Schrattenholzer (2006) compare the results of allocation based on equal per capita emission allowances with an allocation based on equalizing carbon emission intensity (per unit of economic activity) across countries, and note that the two rules impose substantially different abatement targets on countries. Böhringer et al. (2002)

[2]Separating common interests from particular positions is a strategy for effective (principled) negotiation (Fisher and Ury, 1981).

estimate the impact of alternative burden allocation schemes on the European Union countries using a computable general equilibrium model, and find that actual allocation of emission burden to comply with the EU's overall Kyoto commitment does not mimic allocation that would emerge from maximizing standard social welfare functions with alternative degrees of inequality aversion. Böhringer and Welsch (2006) simulate a 'contraction and convergence' allocation of emission permits at the global level, where permits are initially allocated based on historic emissions and a transition is made to equal per capita emission allocations over time. They conclude that tradability of allocated permits is central to relax the burden sharing problem across world regions. Böhringer and Helm (2008) conduct a similar analysis, but impose 'welfare bounds' to ensure that no countries experience windfall gains from the burden sharing process.

We begin by describing the issue of climate change burden sharing, as well as the specific policy context in Canada in Section 2. We then describe the model and data that we use for analysis of the burden sharing issue in Section 3. Section 4 presents the results of our analysis, and Section 5 concludes.

# 2 Burden sharing and the Canadian policy context

### Historic approach to burden sharing in Canada

Canada and its provinces have struggled with sharing the burden for climate change mitigation for nearly two decades. Prior to signing the Kyoto Protocol in 1997, Canada and its provinces engaged in extensive discussions about the appropriate national target for greenhouse gas mitigation. Emerging from these discussions was an agreement between almost all provincial and federal energy and environment ministers that Canada would aim to stabilize its emissions at 1990 levels by the year 2010. Shortly thereafter, Canada's then Prime Minister unilaterally announced that Canada would cut its emissions by 3% relative to 1990 levels by 2010. During the Kyoto Protocol negotiations, the federal government further tightened its target to maintain nominal parity with the European Union and US, promising to reduce emissions by 6% relative to 1990 over the 2008-2012 period. These unilateral moves by the federal government contributed to a breakdown in federal-provincial climate policy negotiations (Macdonald and Smith, 1999). To placate the premiers, in a subsequent First Ministers meeting, the Prime Minister assured the provinces that "no region [would be] asked to bear an unreasonable burden," a phrase that, despite its ambiguity, has shaped intergovernmental negotiations on climate policy ever since (Harrison, 2007). Indeed, a primary reason for the lack of domestic climate policy implementation at the federal level is concern over the strain in federal-provincial relations that would result. Failure to address the burden sharing issue will make future deep cuts in emissions equally unlikely to succeed.

Canada is not the first federation to grapple with burden sharing in the climate change context.[3] During the Kyoto Protocol negotiations, lengthy discussions focused on relative stringency of commitments for emission reduction amongst developed countries (as listed in Annex B of the protocol). The European Union negotiated its Kyoto Protocol commitment as a single entity, so following the Kyoto negotiations, subsequent EU-internal negotiations were initiated to divide the EU's mitigation burden amongst member states.[4] Other federations must also address burden sharing, either implicitly or explicitly, in addressing climate change.

However, climate mitigation burden sharing in Canada may be singularly challenging, for several reasons. First, the significant geographic heterogeneity in emissions intensity across regions in Canada is unparalleled in other federations. Figure 1 shows Lorenz curves capturing the distribution in regional greenhouse gas emissions in several major federations. Unlike Canada, in most federations, individual states have per capita emissions that are relatively similar to one another. In Canada, per capita emissions in Alberta and Saskatchewan are many times higher than in Quebec, and emissions trends suggest a widening gap in the future. The Gini coefficient summarizing the distribution of emissions between regions in Canada is consequently substantially higher (0.29) than in other regions (e.g., in EU, the Gini coefficient is 0.112). This makes mitigation burden sharing much more difficult, since - as we will show - allocation of emission burden based on certain

[3]Burden sharing considerations arise in other domains as well. Olson and Zeckhauser (1966) describe burden sharing amongst NATO countries, and Griffin (1985) focuses on sharing the burden of oil extraction constraints amongst OPEC member states.

[4]In this case, the burden sharing negotiations were informed by to so-called 'Triptych' approach, where economic structure of each country is accounted for by decomposing overall emissions in each country into three sectors (heavy industry, power generation, residential) and applying uniform targets at the sector level that were then summed up to a country's total emission allowance (Phylipsen et al., 1998).

reasonable principles places higher relative burden on some sub-national jurisdictions than others. In contrast, in federations with more homogeneous emissions intensity across sub-national levels, the choice of burden-sharing regime is much less important (Rose and Zhang, 2004).

An additional factor complicating burden sharing in Canada is that while the federal government has the power to sign international treaties, it lacks the automatic power to enforce them. This stands in contrast to most other federations, where the senior level of government is granted the power to comply with a treaty it signs. For example, ratification of a treaty by the US federal government confers to that level of government the power to pass legislation necessary to comply with the treaty in areas that would normally fall under exclusive state authority. Likewise, in Australia, the constitution has been interpreted to suggest that treaty signature by the federal government implies the possibility of federal legislation in areas that normally fall under state jurisdiction (Michelmann and Soldatos, 1990).

Rather than spurring an open debate, the difficulties posed by equitable burden sharing seems to paralyze Canadian climate policy. For example, federal government regulatory proposals for climate change have included little or no discussion of potential impacts at a provincial level. In addition, Canada's main venue for federal-provincial environmental policy discussions - the Canadian Council of Ministers of the Environment (CCME) - does not discuss climate change or potential burden sharing arrangements, despite being seemingly well placed to do so.[5]

### Burden sharing rules

The main part of our analysis is concerned with comparing alternative rules for the sharing the burden of climate change mitigation effort throughout the Canadian federation. We use Canada's Copenhagen commitment, which calls for a 17 percent reduction in greenhouse gas emissions relative to 2005 levels by 2020, to illustrate the challenges with environmental burden sharing in Canada. It should be emphasized that similar concerns over burden sharing have rendered past emission reduction targets difficult politically, and that for proposed 'deep' greenhouse gas targets that

[5]The CCME's objective is to focus on environmental issues that are "national and intergovernmental in nature, and of interest to a significant portion of CCME member jurisdictions." Although climate change mitigation seems like a logical addition, it is not included amongst CCME priorities. See `http://www.ccme.ca/ourwork/`.

Canada has subscribed to by mid-century, success in addressing the burden sharing issue will play a pivotal role in determining whether such targets can be met.[6]

Our analysis of burden sharing is conducted with a computable general equilibrium model of the Canadian economy, which is described in the following section of the paper. Different burden sharing scenarios are implemented in the model through the allocation of emission permits, $z_r$, to provinces, $r$. Each permit grants the right to emit one unit of greenhouse gas emissions. Permits are initially allocated to the representative household in each province, and can be sold to emitters and traded between emitters. To make scenarios comparable, in each burden sharing scenario we simulate, the sum of emission permit allocations across provinces is equal to the Copenhagen commitment.

To structure our burden sharing analysis, we draw partly on and operationalize previous definitions of equity criteria for allocating emissions burden, as shown in Table 1. These rules are based on general principles, which we believe are well suited as a basis of negotiation. Two categories of burden sharing rules are identified. *Ex ante*-based allocation rules define fairness in emission permit allocation from the perspective of the economic, social, or environmental conditions that exist in different regions prior to implementation of the emission mitigation policy under consideration. Denoting benchmark income (or consumption), population, and emissions in region $r$ as $y_r^0$, $p_r^0$, and $z_r^0$, respectively, *ex ante*-based allocation rules are of the form $z_r^{\text{ex ante}} = z_r^{\text{ex ante}}(y_r^0, p_r^0, z_r^0)$ (where for simplicity and following the literature, we only consider three differentiating features of provinces - emissions, population, and income). In contrast *ex post*-based allocation rules define fairness in emission permit allocation from the perspective of regional well-being after policy implementation. *Ex post*-based allocation rules are of the form $z_r^{\text{ex post}} = z_r^{\text{ex post}}(y_r^0, y_r^1)$, where $y_r^1$ reflects economic conditions in the new equilibrium that results after the emission reduction policy is in place (our model does not account for inter-regional migration, so $p_r^0 = p_r^1$).[7] While it is possible to determine *ex ante* permit allocations without the use of an economic model, determining *ex post* allocations

[6] Canada has committed to reducing greenhouse gas emissions between 50 and 60 percent below 2005 levels by 2050, which corresponds to around a 80 to 90 percent reduction from 'business as usual' levels, assuming continued growth in economy and emissions.

[7] Rose et al. (1998) refers to *ex ante* and *ex post* burden sharing rules as allocation-based and outcome-based, respectively. Kverndokk and Rose (2008) provide a more elaborate description of philosophical principles underlying many of the rules that we discuss.

clearly requires a model that can capture the economic responses to introduction of an emission policy. We use the model described in the following section to compare permit allocation and welfare impacts of a number of *ex ante* and *ex post* rules for sharing emission reduction commitments amongst Canadian provinces.

Amongst the set of possible *ex ante*-based rules, allocating abatement effort according to an *egalitarian* criterion is perhaps the most natural and common definition of equity. Implicit in this definition is the assumption that all individuals have equal claims over atmospheric assimilative capacity, such that pollution rights should be distributed on an equal per capita basis. Using the notation given above, an egalitarian allocation of emission permits would be formalized as:

$$z_r^E = (1-t)\frac{p_r}{\sum_s p_s}\sum_s z_s^0,$$

where $r, s$ denote the set index across all provinces, and where $t$ is the target fraction of benchmark national emissions to be cut. The total quantity of emission permits allocated to all provinces is $(1-t)\sum_s z_s^0$, which is a fraction $t$ less than benchmark emissions, and which is constant across all burden sharing rules that we evaluate. In the *egalatarian* rule, this total is allocated to provinces according to their share of the national population.

In contrast to this definition, the *sovereignty* criterion asserts that the current or past flow of emissions constitutes a right to produce emissions (Rose, 1992). Allocating emission permits under a sovereignty criterion would involve equal relative cutbacks in emissions by all provinces, such that:

$$z_r^S = (1-t)z_r^0.$$

Under this criterion, each province receives an allocation that is a fraction $t$ less than its benchmark emissions.

Differences in incomes imply that different regions have different abilities to pay for greenhouse gas reductions. Under an *ability to pay* criterion, emissions abatement effort would be distributed in proportion to ability to pay. We formalize this by allocating the emissions reduction burden in proportion to benchmark per capita income, $\frac{y_r^0}{p_r}$, in each province, such that each province's emission allocation is given by:

$$z_r^A = z_r^0 \left( 1 - t \frac{\frac{y_r^0}{p_r} \sum_s z_s^0}{\sum_s \frac{y_s^0}{p_s} z_s^0} \right).$$

This burden sharing formula sets the emission reduction target in each region in proportion to per capita gross domestic product.[8] Thus, if region A has twice the per capita economic output of region B, it will be allocated an emission reduction target (in percentage terms) twice as stringent as that of region B.

Under *ex ante*-based rules, the allocation of emission permits is based on initial attributes of regions. In contrast, under *ex post*-based rules, the allocation of emission permits is chosen to satisfy some objective function that depends on economic responses to the emission restriction. In this paper, we implement *ex post*-based allocations of emission permits using the mechanism of a social welfare function (Atkinson, 1970). We use a simple social welfare function which exhibits constant relative inequality aversion, in which social welfare is given by:

$$SWF = \frac{1}{1-\rho} \sum_r p_r U_r^{1-\rho}$$

where $U_r$ is money-metric per capita welfare in model region $r$, and $\rho$ is a parameter that captures inequality aversion. The allocation of permits $z_r$ is chosen to maximize the value of the social welfare function.[9] We run the model with several different values of $\rho$. A value of $\rho = 0$

[8] Alternatively, the term in brackets could be raised to a power to make the relationship between benchmark per capita income and emission allowances non-linear.

[9] There is a similarity between the ability to pay rule described above and these ex post rules, both of which base permit allocations on relative well-being. However, they are distinct in that the ability to pay rule is based only on ex ante income levels, while the ex post rules are concerned with the impact of the climate policy on equilibrium welfare.

corresponds to social preferences that are agnostic to distribution of policy costs, thereby adopting a utilitarian (Benthamite) perspective on efficiency. A value of $\rho = 1$ is equivalent to a horizontal equity criterion, where the objective function entails equalizing the percentage change in utility across regions. When $\rho = \infty$, the utility function is Rawlsian, such that emission permit allocation is chosen to maximize the welfare of the poorest region in the model. In numerical simulations that follow, we use a value of $\rho = 10$ to reflect the Rawlsian perspective on equity.

We implement each of the scenarios described above by distributing permits for emitting greenhouse gases to the Canadian provinces. Permits are assigned to the representative agent in each province. Each unit of emissions released then requires an accompanying emission permit, which must be acquired from the representative agent.[10] Emission reduction (described in the following section) takes place in a cost-minimizing manner, where marginal abatement costs are equalized across emission sources. The price of emission permits is endogenous in the model.

An important consideration that impacts both the equity and the efficiency of alternative burden sharing rules is whether these permits can be traded between provinces. Currently, many policies implemented or countenanced in Canada for the reduction of greenhouse gases do not allow regulated entities to trade permits with one another. However, some policies, such as recently implemented regulations governing light-duty vehicle efficiency and renewable fuel blend ratios, do allow permit trading. In order to maintain the focus on the equity dimension of burden sharing rules, in our main simulations we allow inter-provincial permit trading. However, we also provide some results corresponding to the assumption that permits are not tradable between provinces. Not surprisingly, we find that eliminating trade in emission permits between provinces substantially reduces flexibility in abatement effort, and increases the cost associated with meeting a given target. With higher costs, burden sharing is likely to become even more contentious.[11]

In addition to the prospective examination of alternative burden sharing rules, we also assess implicit burden sharing implications of currently proposed emission reduction targets that have

[10] The policy we simulate is equivalent to a cap and trade system or carbon tax that covers all emissions of carbon dioxide. We therefore do not consider an accompanying offset program.

[11] In addition, the nature of the policy - whether market based or command and control - is important. With command and control or other inflexible policies, costs of compliance increase further. In this paper, our focus is on market-based regulations, so we neglect this dimension of the problem.

been adopted by provincial governments.

## 3 The model

To investigate the economic implications of emission regulation in Canada, we use a static multi-sector, multi-region computable general equilibrium (CGE) model of the Canadian economy. The CGE approach builds upon general equilibrium theory that combines price-responsive supply and demand reactions of rationally-behaved economic agents with the analysis of equilibrium conditions. The rigorous microeconomic foundation of market interactions within an economy-wide setting makes it possible to address both efficiency as well as distributional impacts of policies. This section includes a non-technical overview of the model. A more detailed and formal model description is provided in the algebraic model summary. In addition, a complete set of model files (written in the GAMS/MPSGE language) is provided as an electronic annex to this article available on the journal web site.

The model captures characteristics of provincial (regional) production and consumption patterns through detailed input-output tables and links provinces via bilateral trade flows. Each province is explicitly represented as a region, except Prince Edward Island and the Territories, which are combined into one region. The representation of the rest of the world is reduced to import and export flows to Canadian provinces which are assumed to be price takers in international markets. To accommodate analysis of energy and climate policies the model incorporates rich detail in energy use and greenhouse gas emissions related to the combustion of fossil fuels.

The model features a representative agent in each province that receives income from three primary factors: labour, capital, and fossil-fuel resources.[12] There are three fossil resources specific to respective sectors, namely, coal, crude oil and gas. Fossil-fuel resources are specific to fossil fuel production sectors in each province. Labour is treated as perfectly mobile between sectors within a region, but not mobile between regions. Capital is treated as partially mobile between sectors and provinces, a point we elaborate on below. The model incorporates details of direct and indirect

[12] Land use associated with agricultural production and forestry is therefore not explicitly accounted for, but instead treated as part of the specific capital stock of the relevant sector.

taxes which are received by the provincial or federal governments in order to finance public services.

The choice of sectors in the model has been to keep the most carbon-intensive sectors in the available data as separate as possible. The energy goods identified in the model include coal, gas, crude oil, refined oil products and electricity. This disaggregation is essential in order to distinguish energy goods by carbon intensity and the degree of substitutability. In addition the model features major energy-intensive industries which are potentially those most affected by emission reduction policies. Tables 2 and 3 provide a summary of the regions and sectors included in the model.

## Production

Production of commodities in each region, other than primary fossil fuels, is captured by multi-level constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labour, energy and materials (Figure 2). At the top level, a CES composite of non-energy intermediate material demands trades off with an aggregate of energy, capital, and labour subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labour and capital. At the third level, capital and labour substitution possibilities within the value-added composite are captured by a CES function. Values for the elasticities of substitution between capital and labour, as well as between value added and energy differ by sector and are drawn from the econometric work of Okagawa and Ban (2008).[13] The aggregate energy input is defined as a CES function of electricity and the composite of coal, oil and gas. At the fourth level the composite coal, oil and gas is a CES function of coal and a CES aggregate of oil and gas. Output produced in each sector is supplied to each of the domestic regions and the rest of the world. Given the ratio of regional and international prices a constant elasticity of transformation (CET) function determines price- responsive quantities supplied to each province and the international market.

[13]We test the impact of an alternative nesting structure in which labour is combined with a CES aggregate of capital and energy, also based on econometric estimates from Okagawa and Ban (2008). We also test the impact of replacing the econometrically-estimated elasticities from Okagawa and Ban (2008) with those from Dissou et al. (2012) (these results are not included in this paper, but are available upon request). This results in a total of four alternative production function specifications (two different nesting structures and two different sets of econometric estimates). Neither of these choices result in a significant change in any of our results. In particular, our qualitative conclusions remain unchanged.

In the production of fossil fuels (coal, crude oil and natural gas), the production function is similar to that described above, except the capital-labour-energy-materials aggregate is combined with a fossil fuel specific resource at the top level (Figure 3). The elasticity of substitution between this sector-specific resource and the other inputs is calibrated to reflect empirical evidence on fossil fuel supply elasticities as described in Rutherford (2002).

In all of the simulations we consider, we take technology as exogenous. That is, firms can move along isoquants in response to changes in (relative) prices, but isoquants are fixed. This assumption effectively rules out innovation as a response to changes in emission prices. This can have impacts on model results, but we feel the assumption is justified for a number of reasons: (1) the theoretical literature on induced technological change is quite diverse without providing unambiguous guidelines for representing complex mechanisms on invention, innovation and diffusion in CGE models (see Schwark, 2010); (2) a focus on modeling innovation would go at the expense of other details that appear relevant in our context such as the level of regional/sectoral disaggregation; (3) empirical data for the parameterization of innovation mechanisms is lacking.

### Final consumption, leisure and savings

In each province a representative household maximizes welfare subject to a budget constraint. Total income of the representative household consists of net factor income and transfers. The representative agent in each region receives welfare from leisure and consumption which trades off at a constant elasticity of substitution. The latter is calibrated to reflect empirical evidence on labor supply elasticities. Specifically, we use the process described in Ballard (2000) to set the elasticity of substitution between leisure and consumption as well as the benchmark budget share of leisure based on empirically estimated labour supply elasticities. For these, we use values of 0.05 and 0.3 for the uncompensated and compensated labour supply elasticities, respectively ((Cahuc and Zylberberg, 2004). Consumption[14] is given as a CES composite that combines consumption of composite energy and an aggregate of other (non-energy) consumption goods. Substitution patterns within the energy bundle as well as within the non-energy composite are reflected by means of CES

[14]See also Figure 2 which reflects the production of the composite consumption good as well.

functions. Investment demand is exogenous and determines savings of the representative household.

### Government

Government demand within each region is fixed at exogenous real levels. The federal and provincial governments receive taxes to finance public expenditures. Public surpluses or deficits are balanced through lump-sum transfers with the representative households. The model includes detailed accounting for the existing tax structure. In particular, it incorporates direct personal and corporate income taxes with tax rates set to reflect effective marginal tax rates as determined by Mintz et al. (2005). It also includes indirect production and product taxes differentiated by sector, as well as sales taxes on final demand.

### Trade

Bilateral trade between provinces is specified following the Armington (1969) approach, which distinguishes domestic and foreign goods by origin. All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported goods from other provinces and the rest of the world (Figure 4).

All Canadian provinces are assumed to be price takers in the world market. There is an imposed balance of payment constraint between Canada and the rest of world aggregate. To implement this constrain, we fix the current account surplus exogenously at the benchmark level.

### Primary factors of production

The representative agent in each province is endowed with labour, capital, and fossil fuel resources. Based on the real wage rate and income, the agent chooses how much labour to supply to the labour market and how much to consume as leisure. Labour supplied to the labour market is perfectly mobile between sectors, but immobile between regions. The assumption of labour immobility between regions is a simplification reflecting empirical evidence on rather limited mobility of labour compared to capital.[15]

[15] Note that the real wage rate between provinces does not differ substantially as a result of the emission policies we apply, so any labour mobility function based on wage differentials would result in very small predictions of labour

Capital endowments are exogenous. A portion of capital is immobile - fixed in the sector and region in which it is installed in the benchmark.[16] The remainder of the capital endowment is mobile, both between regions and between sectors. This treatment of capital is sometimes referred to as a putty-clay assumption. Additionally, the country can borrow or save on the world capital market at a constant rate of interest. The current account is fixed at the benchmark level, such that an inflow of capital to the country must be financed by a balance of trade surplus and vice versa.

Fossil fuel resources are exogenous and and elasticities of substitution in the resource extraction sectors are calibrated to match exogenous estimates of the resource supply elasticities. Fossil fuel resources are specific to both sectors and regions. Land is not represented specifically as a resource in non-fossil fuel sectors (agriculture, forestry) but is instead treated as a portion of the overall capital stock in these sectors.

### Emissions

As to the representation of greenhouse gas emissions, we focus on $CO_2$, which is by far the most important greenhouse gas in Canada, accounting for roughly 80 percent of total emissions. Carbon dioxide ($CO_2$) emissions are linked in fixed proportions to the use of fossil fuels, with $CO_2$ coefficients differentiated by the specific carbon content of fuels. In the benchmark (no-policy) scenario, there is no limit on fossil fuel emissions, and thus no value associated with emission abatement. In the counterfactual scenarios, a limit is placed on total carbon dioxide emissions. An emission permit must be remitted to the representative agent each time a unit of carbon dioxide is released to the atmosphere. The limited number of available emission permits (as described above, the limit is consistent with Canada's Copenhagen commitment) results in emission permits gaining economic value and provides incentive for firms and individuals to reduce carbon dioxide emissions. Permit trade is unrestricted between sectors. In our central case simulations, we allow for permits to

mobility.

[16] In the runs reported here, 50% of the total capital stock is considered fixed at the sector-region level, mimicking a mid-term horizon for impact assessment. We conduct sensitivity analysis on this parameter (not reported here) and find no qualitative change in the results and only a small quantitative change in the results as we vary the proportion of capital fixed at the sector-region level.

be traded between provinces (the implications of restricting permit trade between provinces are discussed as part of the sensitivity analysis). In all scenarios, emission permits are initially allocated to the representative agent in each province according to the burden sharing rules we describe above. These permits are sold to emitters, who require a permit to emit a tonne of $CO_2$. The allocation of emission permits to the representative agent is exactly equivalent to auctioning permits to emitters and rebating all revenue to households in lump sum.

The price of emission permits is endogenous in the model, and is determined from the equilibrium of supply and demand in the market for emission permits. Note that we would obtain identical results by simulating a carbon tax (at the same price level) in which all tax revenues were returned in lump sum to the representative household in each province.

Emissions abatement can take place through a number of pathways. Firms can substitute low-carbon fuels (such as natural gas or electricity) for high-carbon fuels (such as coal). This substitution is governed by elasticities of substitution $\sigma^{OIL}$, $\sigma^{COA}$ and $\sigma^{ELE}$, as shown in Figure 2 as well as by benchmark cost shares of fuels, which are derived from economic accounts data. Substitution of non-energy inputs for energy inputs can also occur. With the production function as illustrated in Figure 2, the rate of substitution is governed by elasticities $\sigma^{E}$, $\sigma^{L}$, and $\sigma^{M}$. Finally, emission reduction can occur through changes in economic structure or scale. For example, a carbon policy that reduces the productivity of a dirty sector will cause primary factors to be drawn to other sectors of the economy and result in a shift in sectoral composition. Likewise, if if the carbon policy causes a reduction in overall production and demand, this scale reduction will result in a commensurate drop in carbon emissions.[17]

### Parametrization

The model is based on 2006 provincial (symmetric) input-output data at the S-level of aggregation Statistics Canada (2006a,b). Energy-intensive sectors are further split down from the S-level using more disaggregate information on input-output relationships from the national L-level input-output

[17] Formally, the demand for energy in any sector (which is directly linked to emissions as described above) can be determined from the profit function of the relevant production sector. The profit function for each sector is given in the Appendix (equations 1-4). The demand for each energy good is a function of the prices of all inputs to the production function as well as benchmark cost shares and elasticities of substitution.

accounts as well as output data from Environment Canada's in-house model Energy2020 (ICF International, 2010). Sectoral energy inputs and emissions of greenhouse gases by province are provided by Energy2020.

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis. The base year input-output data determines the free parameters of functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behaviour of the economic agents. The responses of agents to price changes are determined by a set of elasticities listed in Table 4. Sources for the elasticities are as discussed in the text.

Actual policy proposals for emissions reduction in the national and international context are predominantly stated with respect to 2020 as the future compliance year. To provide policy-relevant ex-ante impact assessments for Canada we thus need to construct a hypothetical business-as-usual reference situation in 2020 where no emission regulation applies. We do so by forward-calibration of the 2006 base year data set to Energy2020 projections of economic growth and energy demand.[18] Thus the calibrated 2020 benchmark data implicitly includes forecasts of technological change or autonomous energy efficiency improvements that are part of the Environment Canada benchmark forecast.

Table 5 shows summary data describing the model projection. The resource and emission-intensive provinces of Alberta, Saskatchewan, the Territories, and Newfoundland are all projected to have greenhouse gas emissions and incomes above the national average. In the absence of policy, Alberta, Nova Scotia, and Saskatchewan's electricity sectors remain substantially fired by coal, resulting in a high greenhouse gas intensity relative to the national average.

[18] A detailed description of the forward-calibration technique can be found in Böhringer et al. (2009).

# 4 Results and discussion

## 4.1 Main results

All of the burden sharing scenarios we explore are conducted for the year 2020. Canada's international commitment for this year entails a 17 percent reduction in greenhouse gas emissions relative to 2005, negotiated as part of the Copenhagen Accord (but also advanced as a domestic target prior to the Copenhagen meeting). Because of projected growth and changes in structure in the Canadian economy between 2005 and 2020, the real required reduction in emissions relative to the unregulated baseline in order to hit this target could be different than 17 percent. We use the forward-calibrated model, which reflects the most up-to-date projections made by Environment Canada for emissions and economic structure in 2020 (Environment Canada, 2012), to project that Canada's Copenhagen commitment requires a cut from business as usual emissions of about 17.6 percent in 2020.[19]

As described above, in order to maintain our focus on the equity dimension of burden sharing rules, we treat emission permits as tradable between provinces in our central case simulations. In a later section, we eliminate this 'where' flexibility, which significantly increases the costs associated with meeting a given national target and exacerbates the regional differences in welfare resulting from different burden sharing rules.

#### Allocation of emission burden

Table 7 shows allocation of emission permits under the different burden sharing rules. Values for *ex ante*-based rules (left-hand panel of Table 7) directly follow from projected target year statistics in 2020, whereas values listed for *ex post*-based rules are the result of model based general equilibrium responses.

With the sovereignty burden-sharing rule, each province receives an allocation that is equivalent to a 17.6 percent cut in emissions from a business-as-usual level, the amount by which Canadian

[19]Environment Canada (2012) reports a mid-range scenario for business-as-usual emissions in 2020 of 745 million tonnes (p. 18). 2005 emissions were 740 million tonnes. A 17 percent reduction in 2020 emissions relative to 2005 levels thus reflects a 17.6 percent reduction relative to projected business-as-usual emissions.

emissions need to be cut in aggregate to comply with Copenhagen Accord commitments.[20] Although this rule implies a uniform cut relative to business as usual emissions, it imposes significant heterogeneity in emission allowance distribution in per capita terms. For example, Alberta would receive more than six times as many emission permits on a per capita basis than Quebec.

In contrast, an equal per-capita emission allocation distributes the same amount of emission permits to each person, such that there would be significant heterogeneity in allocations relative to projected business as usual emissions. Certain provinces, including British Columbia, Manitoba, Ontario, and Quebec, where per capita emissions are low relative to the national average, would receive emission permits in excess of their requirements. Other provinces, including especially Alberta, Saskatchewan, and the Rest-of-Canada aggregate, would receive significantly less emission permits than business as usual emissions. In Alberta's case, an equal per capita allocation would imply the province would only receive allocations equal to 25 percent of its business as usual emissions.

Under an ability to pay criterion, Alberta and the rest-of-Canada aggregate, which have the largest per capita incomes, would be allocated a lower number of allowances than British Columbia, Manitoba, Ontario, Quebec, New Brunswick, and Nova Scotia, which have lower per capita incomes. However, in this case, allocation of emissions permits to provinces is relatively close to the sovereignty scheme, since incomes are relatively similar across Canadian provinces and territories.

In the case of the *ex post*-based burden sharing rules, allocation of permits is endogenously determined in order to maximize a social welfare function with a specified degree of inequality aversion. When the coefficient of inequality aversion, $\rho$, is equal to unity, permit allocations are endogenously determined such that each province experiences an equivalent relative decline in per capita consumption. Following the literature, we refer to this as horizontal equity. Provinces with the ability to easily substitute away from carbon thus receive lower permit allocations than provinces for which substitution away from carbon is more expensive. Substitution away from fossil emissions is generally less costly in regions that have a high emissions intensity, since the marginal

[20] An alternative way to impose the sovereignty rule would be to allocate each province 17 percent less emission permits than 2005 emission levels. Results will differ depending on whether emission growth to 2020 is concentrated in particular provinces, or proportional to 2005 emission levels.

cost of emission abatement is increasing in the quantity of emissions abatement. As a result, the provinces with low starting emissions (British Columbia, Manitoba, Quebec, Ontario) receive a greater allocation of emission permits (relative to business as usual) compared to provinces with high starting emissions, since emissions abatement in these regions is more costly than in regions where starting emissions intensity is high (e.g., Alberta, Saskatchewan).

In the case of the utilitarian social welfare function ($\rho = 0$), permits are allocated in order to maximize aggregate cross-province consumption independent from its distribution across provinces. In practice, this does not lead to a large deviation in allowances compared with the horizontal equity criterion. In the case of the Rawlsian social welfare function ($\rho = 10$), permit allocations are chosen to minimize welfare losses of the poorest provinces, which generates high allocations relative to business as usual emissions for Quebec, British Columbia, and Manitoba, and Ontario, and low allocations for the Rest-of-Canada aggregate and for Alberta, Saskatchewan, and Newfoundland.

**Welfare impact of burden sharing rules**

Table 8 shows the change in welfare resulting from the application of alternative burden sharing rules. As is customary in applied general equilibrium analysis, we measure welfare impacts in terms of Hicksian equivalent variation in income. This measure denotes the amount which is necessary to add to (or subtract from) the benchmark income of the household so that she enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of *ex ante* relative prices.

Under the sovereignty rule, each region receives 17.6 percent fewer permits than its business as usual emissions. Relative welfare effects are driven by differences in the shapes of provincial marginal abatement cost curves. Provinces which have flat marginal abatement cost curves can easily substitute away from $CO_2$ emissions and export excess allocations. Provinces that have steep marginal abatement cost curves find it relatively expensive to reduce emissions and thus tend to become importers of emission rights. Some of the lowest cost opportunities for reducing emissions are in the electricity sector, and involve replacing or retrofitting coal-fired power plants with natural gas plants. As a consequence, provinces with significant coal-fired power generating capacity - notably Alberta and Saskatchewan - fare well under the sovereignty allocation, reflecting their comparative advantage in emission abatement. For both of these provinces, welfare is nearly unchanged compared to the no policy scenario under the sovereignty burden sharing rule. Conversely, provinces with already clean electricity sectors - British Columbia, Manitoba, Ontario, and Quebec - suffer welfare losses from the sovereignty allocation. In retrospect, the sovereignty rule penalizes provinces that have acted early to cut emissions, should these reductions not be credited through downward-adjusted abatement targets.

Under the equal per capita rule, provinces receive a permit allocation in proportion to population. Provinces with business as usual per capita emissions above the national average therefore receive a low allocation relative to emissions and import permits from provinces with low per capita emissions. The result is a transfer from provinces with high per capita emission to provinces with low per capita emissions, with consequent impacts on welfare. The prime example is Alberta, which incurs a welfare loss of about 3 percent under a per capita allocation. Similar, but somewhat smaller, effects occur in Saskatchewan and the Rest of Canada aggregate, which also have high per capita emissions. In contrast, Ontario, British Columbia, Quebec, and Manitoba, where business as usual per capita emissions are substantially below the national average, can increase welfare by selling allocated emission permits.

Under an ability to pay allocation, provinces with income per capita above the national average are allocated less emission permits than provinces with low income per capita. Here, Alberta, Newfoundland, and the Rest of Canada aggregate, which have per capita income well in excess of the national average, are allocated correspondingly fewer emission permits. Relative to the sovereignty allocation, these regions therefore experience more distinct drops in consumption welfare. The converse is true for other provinces, which receive face stringent targets.

Finally, the last columns of Table 8 show welfare losses when the emission reduction burden is allocated in order to maximize a social welfare function with alternative degrees of inequality aversion. With $\rho = 0$, the social welfare function reflects a utilitarian perspective which pursues the smallest aggregate welfare loss being agnostic on the distribution of cost incidence. In this scenario, relative (percent) welfare losses from provinces with high per capita income are lower than average, since such provinces are weighted more highly in a utilitarian scheme. When $\rho = 1$, individuals in each province experience by definition an identical relative welfare loss. Finally, when $\rho$ is greater than unity, permit allocations are made such that regions with lower per capita income experience lower welfare losses reflecting the transition towards a Rawlsian perspective where in the extreme only welfare changes of the poorest household matter. In this scenario, welfare losses are concentrated in the richer regions of Alberta and the Rest-of-Canada aggregate, as well as Saskatchewan and Newfoundland. Other regions are favoured by this rule, and experience much smaller changes in welfare.

**Discussion**

There are a number of lessons to be drawn from these results. First, the allocation of emission burden matters. For the simulated cut in emissions of 17.6 percent, the model generated emission permit price is roughly \$50/t $CO_2$.[21] This implies a total value of emission permits of about \$25 billion.[22] The choice of permit allocation therefore reflects a choice of how to allocate approximately \$25 billion in emission permit rents. Clearly, such choices have important impacts on welfare.

Second, amongst the (infinite) set of all possible burden sharing rules, the subset that we consider, which is based on reasonable alternative philosophical perspectives on fairness, still produces a large range of allocations and welfare implications. In Alberta, for example, the rules we consider imply reductions in welfare from between about 3 percent to about -0.05 percent (a gain). In Quebec, the rules we consider imply welfare reductions of about 0.4 percent to -0.3 percent (a gain).

Third, although we consider a large range of potential burden sharing rules, the allocations implicit in the rules we consider generally all have similar qualitative content. In particular, most rules (with the exception of the sovereignty rule) envision a larger role (i.e., more significant emission reductions compared to the projection) for the emissions intensive provinces of Alberta and Saskatchewan and a smaller role for less emissions intensive provinces including Quebec, Ontario, British Columbia, and Manitoba. This is because the rules we consider are based on initial per

[21] The price varies very slightly between simulations, but since there are only small efficiency implications of the different permit allocation schemes we consider, the variation is minimal.

[22] Benchmark emissions are about 600 million tonnes, so the aggregate value of permits is $600Mt \times \$50/t \times (1 - 0.176) \approx \$25B$.

capita income, initial per capita emissions, and the ability of provinces to reduce emissions. In Canada, these variables are highly correlated: provinces with large fossil fuel endowments (Alberta, Saskatchewan, Newfoundland) tend to be wealthier, higher emitting, and have cheaper avenues for emission reduction than other provinces. For example, in Alberta and Saskatchewan, income and per capita emissions are high and at the margin, emission reductions are relatively cheap. In Quebec, Ontario, British Columbia, and Manitoba, income and per capita emissions are low, and at the margin, emission reductions are relatively expensive. All of the burden sharing we consider rules therefore impose a larger burden on Alberta and Saskatchewan than Quebec, Ontario, British Columbia, and Manitoba.

### 4.2 Inter-provincial permit trade restriction

The preceding results were generated by allowing emission permits to be traded between provinces in the model. This assumption is useful, because it allows us to focus on the equity dimension of climate change burden sharing while maintaining overall efficiency (nearly) constant between model runs. However, actual climate policies - in particular those implemented by the provinces themselves - may not allow for significant trade in emission permits between provinces.[23] If compliance with national emission reduction commitments is primarily achieved in a bottom-up manner through provincial actions, then considering the burden sharing issue in the absence of inter-provincial emission permit trade is useful.

Figure 5 shows welfare costs of alternative burden sharing rules when permit trade between provinces is not permitted (hollow symbols), and compares these to the same metric when permit trade is permitted (solid symbols). We focus just on *ex ante* rules in order to limit clutter in the figure and because the allocations implicit in these rules span the range of all rules we consider. Depending on the rule by which emission permits are allocated, disallowing permit trade can have a major impact on welfare. For example, under the equal per capita rule, Alberta's welfare cost increases from roughly a 3 percent reduction in the case where permits are fungible between provinces

[23]Several recently adopted federal policies, including renewable fuel regulations, light-duty vehicle regulations, and heavy-duty vehicle regulations, do allow for trading of emission permits. However, to our knowledge none of the existing provincial climate policy initiatives allows compliance based on out-of-province emission reductions.

to a 10 percent reduction in the case where permits cannot be exchanged between provinces. When permits are not tradable between provinces, the equal per capita rule is costly in welfare terms for all provinces compared to other rules. This is because this rule imposes high costs overall by not allocating reductions in emissions efficiently, and these efficiency losses are transmitted across provincial borders. For example, when Alberta's income is reduced under the equal per capita rule with no trading, it impacts welfare in neighbouring provinces since these are linked by trade. A similar finding in the international context is presented in Böhringer et al. (2010). On the other hand, allowing inter-provincial permit trade has only a small impact on welfare under the sovereignty and ability to pay rules. This is because these allocate permits in a roughly efficient manner (i.e., roughly equalizing marginal abatement costs across provinces), so there is little role for permit trade.

Figure 6 shows the equilibrium prices of greenhouse gas emission permits in each of the runs. The runs in which trading is allowed are captured by the dashed vertical line, and show a permit price of roughly \$50/t $CO_2$ to achieve Canada's Copenhagen target.[24] When trading is not allowed, permit prices can vary between regions. Depending on the rule, significant variance is possible. For example, under the equal per capital rule, permit prices are over \$500/t $CO_2$ in Alberta, and \$0 in Quebec, Ontario, Manitoba, and British Columbia (i.e., the quota is not binding in these provinces).

Overall, these results suggest unsurprisingly that allowing inter-provincial permit trade can significantly reduce welfare costs of reaching an aggregate emission goal. However, they also suggest that for certain burden sharing rules, allocation of permits to satisfy a certain equity criterion also comes close to an allocation with equal marginal abatement costs. This is encouraging, since most climate policy in Canada currently takes place at a provincial level without a significant role for inter-provincial permit trade. Nonetheless, for more significant reductions in emissions, even small deviations from the equimarginal allocation impose significant welfare costs, and trading between provinces will become more critical.

[24] Efficiency is (nearly) unaffected by alternative permit trading schemes when trading is allowed, as it represents only a transfer between agents. Permit prices are thus (nearly) equal no matter which burden sharing rule is adopted when trading is allowed.

### 4.3 Existing provincial climate change targets

During the last several years, all Canadian provinces have made specific commitments to achieve reductions in emissions by the year 2020 (see Table 6). These emission reduction promises are voluntary commitments, typically presented as part of a climate change action plan, and are sometimes enshrined in legislation.[25] Because they reflect voluntary commitments, they may or may not be achieved (like Canada's Copenhagen commitment). Additionally, existing provincial commitments were formulated over a number of years and were not developed as part of a national dialogue about how to allocate the burden for greenhouse gas reductions amongst the provinces. However, an examination of these voluntary commitments allows us to draw some useful conclusions about the willingness of individual Canadian provinces to contribute to the national emission reduction objective, or in other words to share the burden of reducing emissions.

Table 9 shows estimates of the impact of meeting these targets calculated using our CGE model. We run the model under two scenarios: one in which permits are fungible between provinces, and one in which each province achieves its self-imposed emission target with no trade in emission permits with other provinces. Existing provincial climate change plans generally do not envision a large role for inter-provincial trade in permits before 2020. In each scenario, it is assumed that provincial commitments are achieved in a cost-effective manner (i.e., with a market-based system such as an emission tax or cap and trade system).

The first column of the table reports these commitments as a percentage of projected business as usual emission levels in 2020. In total, commitments made by provinces - if achieved - would result in a reduction in emissions comparable to Canada's Copenhagen commitments, and very similar to the emission reduction targets that we have examined throughout the paper. According to the Environment Canada (2012) forecast to which we calibrate, British Columbia's and Newfoundland's commitments are the most stringent relative to projected 2020 emissions, requiring cuts in emissions of 45 and 59 percent relative to business as usual emissions, respectively. In contrast, most other

[25] British Columbia, for example, has introduced legislation that commits it to reduce emission to 33 percent below 2007 by 2020 (`http://www2.news.gov.bc.ca/news_releases_2005-2009/2007OTP0181-001489.htm`). Quebec introduced similar legislation that required adoption of a target relative to 1990 emissions (`http://www2.publicationsduquebec.gouv.qc.ca/dynamicSearch/telecharge.php?type=5&file=2009C33A.PDF`.

provinces have adopted targets that require much more modest abatement efforts relative to 2020 levels.

We can compare these allocations to the allocations derived from the application of the various burden sharing rules described in the paper.[26] The most striking result is that the individual commitments are not well represented by any of the burden sharing rules we examine.[27] In particular, the two provinces for which the each of the burden sharing rules suggests should receive a relatively stringent target - Alberta and Saskatchewan - opt for a relatively high allocation. In contrast, Quebec and British Columbia, which under each of the burden sharing rules gets a relatively generous allocation, have opted for relatively stringent targets.

The second two columns of the table report the Hicksian equivalent variation in income associated with the existing provincial commitments and the equilibrium emission permit price for a scenario in which permits are tradable between provinces. The final two columns report similar figures for a scenario in which permits cannot be traded between provinces, so each province meets its emission constraint on its own. This scenario is probably most similar to existing provincial climate change plans, which do not have any role for inter-provincial emission permit trade. As can be seen in the final column of the table, the commitments made by provinces vary significantly in stringency between provinces. Our model suggests British Columbia and Newfoundland's targets are both especially stringent, with marginal abatement costs of several hundred dollars per tonne of carbon dioxide. Manitoba and Quebec have also chosen stringent targets compared to other provinces. Again in contrast, Alberta and Saskatchewan, along with Nova Scotia have chosen lax targets relative to other provinces and could likely meet their targets with relatively modest policies. The large spread in marginal abatement costs between provinces if existing provincial commitments are followed through upon highlights the inefficiency of setting targets at a decentralized level if

[26]In making these comparisons, we rely on additional model runs in which burden sharing rules are applied with the same target on aggregate as implied by summing individual province commitments. We do not show these runs here, because they are very similar to those above due to the fact that the individual provincial commitments sum nearly exactly to the national Copenhagen commitment.

[27]In a regression of the actual provincial allocations on all of the burden sharing rules, none of the rules has a coefficient that is close to conventional levels of statistical significance. The linear combination of all of the burden sharing rules explains less than half of the variance in actual emission reduction targets. In separate regressions of the actual commitments on individual burden sharing rules, the $R^2$ value is close to zero in each case, and coefficients on the burden sharing rules are close to zero and in some cases negative. None are statistically significant.

permit trade is not allowed.

## 5 Conclusions

Dividing the burden for greenhouse gas emissions amongst the provinces has proven challenging in Canada, and is likely a major factor contributing to Canada's poor historic performance on greenhouse gas abatement. This paper has argued that such environmental federalism factors are likely to continue to play a major role in the public policy debate in Canada, and that failure to address these burden sharing issues will continue to limit progress in achieving greenhouse gas reductions in the country. Progress on reducing emissions could be facilitated with an explicit analysis of alternative rules for sharing the burden of greenhouse gas reductions amongst the provinces, as is presented here. We believe that while provinces will have difficulty agreeing to particular allocations of burden, they may be more likely to agree on high-level philosophical principles for governing burden sharing, and that these principles could subsequently be applied in the formulaic manner we describe here to allocate burden between provinces.

The paper is based on a sectorally-detailed multi-province general equilibrium model, which is forward-calibrated to the year 2020. Using the model, we consider several archetypal burden sharing rules that emerge from previous literature. The two most common rules considered at the global level, which we refer to as sovereignty and egalitarian rules, impose vastly different obligations on different Canadian provinces. The sovereignty rule treats existing emissions as conferring a de facto pollution right, and so imposes uniform percentage cuts relative to this existing level of emissions. Provinces where emissions can be reduced at low cost thus derive a relative (and sometimes absolute) benefit from this burden sharing rule. Because coal-fired power plants offer one of the cheapest sources of emission reductions, provinces like Alberta and Saskatchewan that obtain a majority of power requirements from coal benefit from this allocation rule. In contrast, provinces that are already relatively 'clean' have less opportunities for low-cost emission reductions and experience higher costs from this allocation rule.

The other environmental burden sharing rule that is both widely discussed and rests on a solid philosophical footing is the egalitarian rule. Under this rule, each individual is permitted an equal amount of pollution, reflecting equal ownership of common property greenhouse gas assimilative capacity. In this case, provinces where per capita emissions are significantly higher than the national average are required to make more dramatic cuts in emissions than others (or to source permits from other provinces, if these are tradable between provinces). Alberta and Saskatchewan, where per capita emissions are several times the national average, thus fare less well under an egalitarian rule, while Quebec and Manitoba, with low per capita emissions, fare much better.

In addition to these *ex ante*-based rules, we also consider several *ex post*-based rules for sharing the burden of emission reduction across members of the federation. These rules allocate emission permits in order to reach certain goals with respect to welfare impacts across provinces. We show that potentially attractive *ex post*-based allocation rules, including Rawlsian, utilitarian, and horizontal burden sharing rules, imply significantly different relative targets across provinces, and consequently different welfare impacts.

The climate change debate in Canada has so far not included a robust discussion of inter-provincial burden sharing. Instead, existing provincial commitments to reduce greenhouse gas emissions have been made in a decentralized environment, with little consideration for the relative burden of different provinces. In particular, emission reduction targets adopted by Alberta and Saskatchewan, provinces with extremely high per capita emissions and income relative to others, are weaker relative to other provinces than would be expected under most of the archetypal burden sharing rules we considered. On the other side, Quebec and British Columbia, provinces with lower per capita emissions and incomes than the national average, have adopted relatively more stringent greenhouse gas emission targets than any of the burden sharing rules we consider would recommend. Although it is not possible to make an unambiguous case for any of the burden sharing rules individually, some combination of the rules we consider should likely form the basis for a 'fair' sharing of the burden of emission reduction throughout Canada. The fact that existing commitments are so far from any of the archetypal burden sharing rules suggests the importance of explicit consideration of these rules in forming commitments, especially for future 'deep' greenhouse gas abatement targets where the stakes will be higher.

# A Tables

| Criterion | Definition | Operational rule | Formula |
|---|---|---|---|
| Ex ante-*based* | | | |
| Sovereignty | Past emissions confer a right to future emissions | Distribute permits in proportion to historic emissions/economic activity | $z_r = (1-t)z_r^0$ |
| Egalitarian | Equal rights to pollute | Distribute permits in proportion to population | $z_r = (1-t)\frac{p_r}{\sum_s p_s}\sum_s z_s^0$ |
| Ability to pay | Burden should vary with well-being | Distribute permits in inverse proportion to GDP per capita | $z_r = z_r^0\left(1 - t\frac{\frac{y_r^0}{p_r}\sum_s z_s^0}{\sum_s \frac{y_s^0}{p_s} z_s^0}\right)$ |
| Ex post-*based* | | | |
| Horizontal equity | Equal relative welfare losses | Distribute permits to equalize welfare/GDP change | $z_r \mid \frac{U_r}{U_r^0} = \frac{U_s}{U_s^0}\ \forall r, s$ subject to $\frac{\sum_r z_r}{\sum_r z_r^0} = 1-t$ |
| Utilitarian | Minimize cost | Distribute permits to minimize aggregate welfare loss | $\max_{z_r} \sum_s p_s U_s$ subject to $\frac{\sum_r z_r}{\sum_r z_r^0} = 1-t$ |
| Rawlsian | Minimize cost to poorest region | Distribute permits to minimize welfare loss to poorest region ($q \in r$) | $\max_{z_r} p_q U_q$ subject to $\frac{\sum_r z_r}{\sum_r z_r^0} = 1-t$ |

Table 1: Burden sharing rules. Categorization adapted from Cazorla and Toman (2001); Grubb et al. (1992); Kverndokk and Rose (2008); Ringius et al. (1998); Rose (1992). In the formulas, $z_r$ is permit allocation, $z_r^0$ is benchmark emissions, $0 < t < 1$ is the national emission reduction target as a fraction of benchmark emissions, $p_r$ is population, $U_r^0$ is benchmark per capita money metric utility, and $U_r$ is per capita money metric utility. $r$ and $s$ index provinces.

| Mnemonic | Region |
|---|---|
| AB | Alberta |
| BC | British Columbia |
| MB | Manitoba |
| NB | New Brunswick |
| NL | Newfoundland and Labrador |
| NS | Nova Scotia |
| ON | Ontario |
| QC | Quebec |
| SK | Saskatchewan |
| RC | Rest of Canada (Nunavut-PEI-Yukon-NWT) |

Table 2: Regions included in the model

| Mnemonic | Sector |
|---|---|
| Gas | Natural Gas |
| CRU | Crude Oil |
| COL | Coal Mining |
| OIL | Petroleum and Coal Products Manufacturing |
| ELE | Electric Power Generation, Transmission and Distribution |
| AGR | Agriculture and Forestry |
| MIN | Other mining |
| CON | Construction |
| PPP | Pulp and paper mills |
| PRM | Primary metal manufacturing |
| CHM | Chemical manufacturing |
| CEM | Cement |
| MFR | Other manufacturing |
| TRD | Wholesale Trade (WHL) and Retail Trade (RTL) |
| TRN | Transportation and Warehousing |
| SER | Services |
| GOV | Government Sector |

Table 3: Sectors included in the model

| Parameter | Value | Description |
|---|---|---|
| *Trade elasticities* | | |
| $\sigma_S^A$ | 4 | Armington substitution elasticity between domestic and imports |
| $\sigma_M^A$ | 8 | Armington substitution elasticity between foreign and other province imports |
| *Production elasticities* | | |
| $\sigma^{KLE-M}$ | varies | Elasticity of substitution between capital-labour-energy and materials |
| $\sigma^M$ | 0 | Elasticity of substitution between materials |
| $\sigma^{KL-E}$ | varies | Elasticity of substitution between capital-labour and energy |
| $\sigma^{K-L}$ | varies | Elasticity of substitution between capital and labour |
| $\sigma^E$ | 0.25 | Elasticity of substitution between electricity and other fuels |
| $\sigma^{C-GO}$ | 0.5 | Elasticity of substitution between fossil fuel inputs |
| $\sigma^{G-O}$ | 0.75 | Elasticity of substitution between oil and natural gas |
| *Consumption elasticities* | | |
| $\sigma_C^{M-E}$ | 0.5 | Elasticity of substitution between energy and other goods |
| $\sigma_C^M$ | 0.5 | Elasticity of substitution between non-energy goods |
| $\sigma_C^E$ | 0.25 | Elasticity of substitution between electricity and other energy |
| $\sigma_C^{C-GO}$ | 0.5 | Elasticity of substitution between fossil fuel inputs |
| $\sigma_C^{G-O}$ | 0.75 | Elasticity of substitution between oil and natural gas |

Table 4: Key parameters in the model. Refer to figures 2 through 4 and the appendix for implementation in model. Production elasticities are from sources described in the text, and vary by sector.

| | Per capita GDP | Per capita CO2 | Manufacturing % of GDP | Fossil Extraction % of GDP | GHG intensity of electricity |
|---|---|---|---|---|---|
| AB | 0.73 | 0.54 | 6.98 | 7.95 | 6.41 |
| BC | 0.45 | 0.11 | 8.11 | 1.27 | 0.29 |
| MB | 0.48 | 0.09 | 13.48 | 0.02 | 0.09 |
| NB | 0.47 | 0.18 | 11.42 | 0.00 | 2.68 |
| NL | 0.63 | 0.20 | 4.74 | 5.16 | 1.22 |
| NS | 0.44 | 0.16 | 8.97 | 0.66 | 5.05 |
| ON | 0.49 | 0.11 | 16.38 | 0.00 | 0.67 |
| QC | 0.47 | 0.08 | 17.69 | 0.00 | 0.13 |
| RC | 0.96 | 0.28 | 2.16 | 5.38 | 0.63 |
| SK | 0.58 | 0.34 | 5.82 | 3.71 | 5.22 |

Table 5: Benchmark projection summary data

| Province | 2020 Target |
|---|---|
| British Columbia | 33% below 2007 level |
| Alberta | 18% above 2005 level |
| Saskatchewan | 20% below 2006 level |
| Manitoba | 15% below 2005 level |
| Ontario | 15% below 1990 level |
| Quebec | 20% below 1990 level |
| New Brunswick | 10% below 1990 level |
| Nova Scotia | 10% below 1990 level |
| Prince Edward Island | 10% below 1990 level |
| Newfoundland and Labrador | 10% below 1990 level |

Table 6: Existing provincial commitments for greenhouse gas reduction in 2020. Source: Environment Canada (2012).

| | *Ex Ante* | | | *Ex Post* | | |
|---|---|---|---|---|---|---|
| | Equal per capital | Sovereignty | Ability to pay | Horizontal equity ($\rho = 1$) | Utilitarian ($\rho = 0$) | Rawlsian ($\rho = 10$) |
| AB | 24.54 | 82.40 | 78.10 | 77.19 | 79.21 | 41.49 |
| BC | 124.32 | 82.40 | 86.54 | 85.89 | 82.15 | 113.69 |
| MB | 147.91 | 82.40 | 85.45 | 88.45 | 87.17 | 116.95 |
| NB | 71.74 | 82.40 | 85.86 | 81.32 | 80.15 | 96.34 |
| NL | 67.64 | 82.40 | 81.03 | 89.90 | 92.76 | 77.02 |
| NS | 81.71 | 82.40 | 86.73 | 86.64 | 84.09 | 104.10 |
| ON | 124.23 | 82.40 | 85.28 | 86.27 | 85.44 | 112.01 |
| QC | 166.24 | 82.40 | 85.81 | 88.07 | 85.38 | 124.66 |
| RC | 47.00 | 82.40 | 71.19 | 89.50 | 95.98 | 0.00 |
| SK | 38.31 | 82.40 | 82.53 | 75.55 | 76.98 | 75.53 |

Table 7: Allocation of permits as percent of projected benchmark emissions.

| | *Ex Ante* | | | *Ex Post* | | |
|---|---|---|---|---|---|---|
| | Equal per capital | Sovereignty | Ability to pay | Horizontal equity ($\rho = 1$) | Utilitarian ($\rho = 0$) | Rawlsian ($\rho = 10$) |
| AB | -3.20 | -0.07 | -0.30 | -0.35 | -0.24 | -2.28 |
| BC | 0.09 | -0.39 | -0.34 | -0.35 | -0.39 | -0.03 |
| MB | 0.25 | -0.41 | -0.38 | -0.35 | -0.36 | -0.06 |
| NB | -0.57 | -0.32 | -0.25 | -0.35 | -0.37 | -0.05 |
| NL | -0.91 | -0.53 | -0.57 | -0.35 | -0.28 | -0.68 |
| NS | -0.46 | -0.43 | -0.35 | -0.35 | -0.40 | -0.03 |
| ON | 0.06 | -0.39 | -0.36 | -0.35 | -0.36 | -0.07 |
| QC | 0.29 | -0.39 | -0.37 | -0.35 | -0.37 | -0.05 |
| RC | -1.42 | -0.53 | -0.82 | -0.35 | -0.18 | -2.65 |
| SK | -1.59 | -0.12 | -0.11 | -0.35 | -0.30 | -0.33 |

Table 8: Hicksian equivalent variation in income measured in percent of projected benchmark income.

| | | Trading | | No Trading | |
|---|---|---|---|---|---|
| | Allocation | Welfare | GHG Price | Welfare | GHG Price |
| AB | 82.5 | 0.0 | 46.1 | -0.6 | 26.6 |
| BC | 55.3 | -0.7 | 46.1 | -1.2 | 279.6 |
| MB | 83.4 | -0.4 | 46.1 | -0.4 | 104.4 |
| NB | 84.2 | -0.3 | 46.1 | -0.5 | 35.8 |
| NL | 41.5 | -1.7 | 46.1 | -4.1 | 395.5 |
| NS | 101.1 | -0.1 | 46.1 | -0.5 | 2.9 |
| ON | 89.6 | -0.3 | 46.1 | -0.5 | 43.7 |
| QC | 78.9 | -0.5 | 46.1 | -0.6 | 103.0 |
| RC | 71.4 | -0.9 | 46.1 | -1.0 | 49.8 |
| SK | 86.8 | 0.1 | 46.1 | -0.4 | 20.6 |

Table 9: Simulation of actual provincial commitments for 2020. The first column shows the commitment made by each province expressed as a percentage of projected benchmark emissions. The second column is the projected change in welfare (Hicksian equivalent variation in income) if all provincial commitments are met with permits tradable between provinces. The third column shows the estimated equilibrium trade price from the model. The fourth and fifth columns repeat the calculations but assuming permits are not tradable between provinces, so that each province achieves its target on its own.

# B Figures

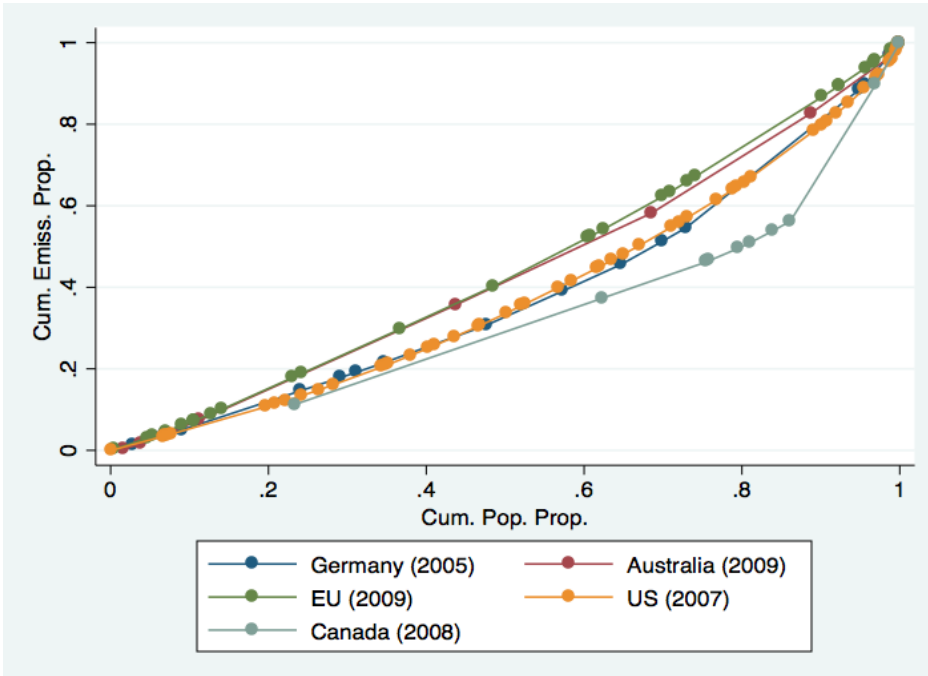


Figure 1: Lorenz curves describing distribution in regional emissions of greenhouse gas for five federations. Each point on each line represents a sub-national jurisdiction (state/province). Australian data for 2009 from `www.climatechange.gov.au` and `www.abs.gov.au`. Canadian data for 2008 from `www.ec.gc.ca` and `www40.statcan.ca`. German data for 2005 from `unfccc.int` and `www.citypopulation.de`. US data for 2007 from `www.epa.gov`. EU data for 2009 from Eurostat. Gini coefficients are: Australia: 0.124; Canada: 0.293; EU: 0.112; Germany: 0.247; US: 0.231.

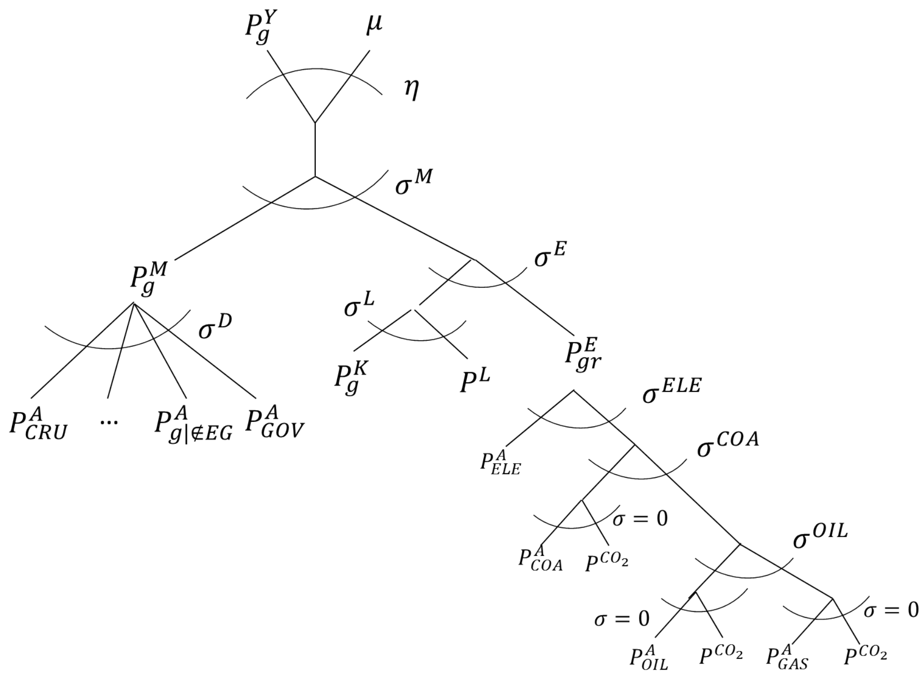


Figure 2: Production function for non-extractive sectors

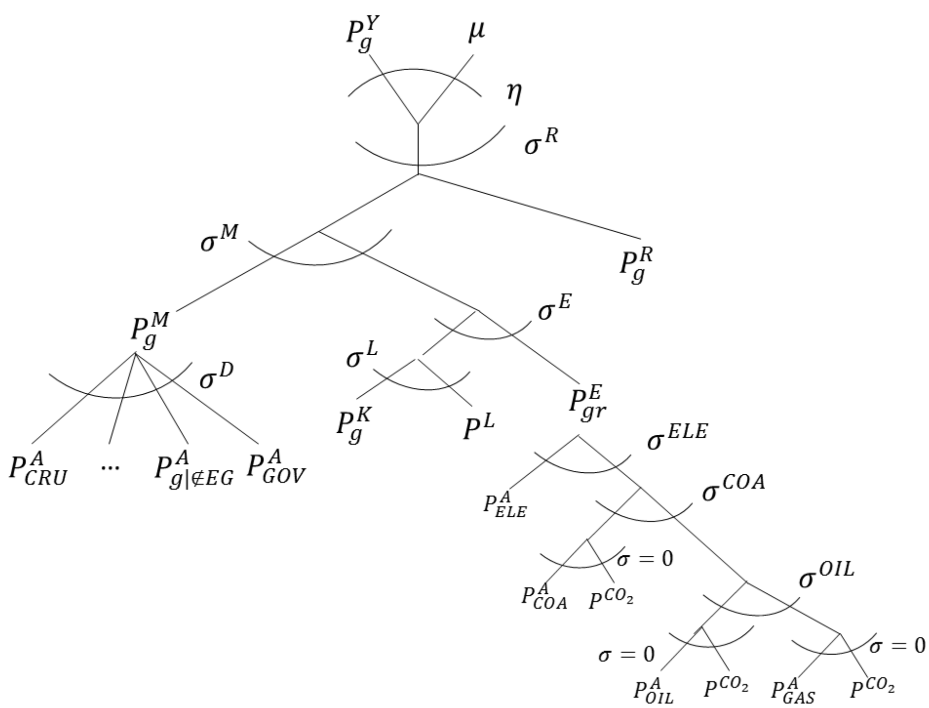


Figure 3: Production function for extractive sectors

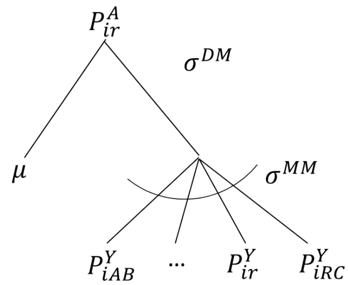


Figure 4: Production of Armington good I in region R.

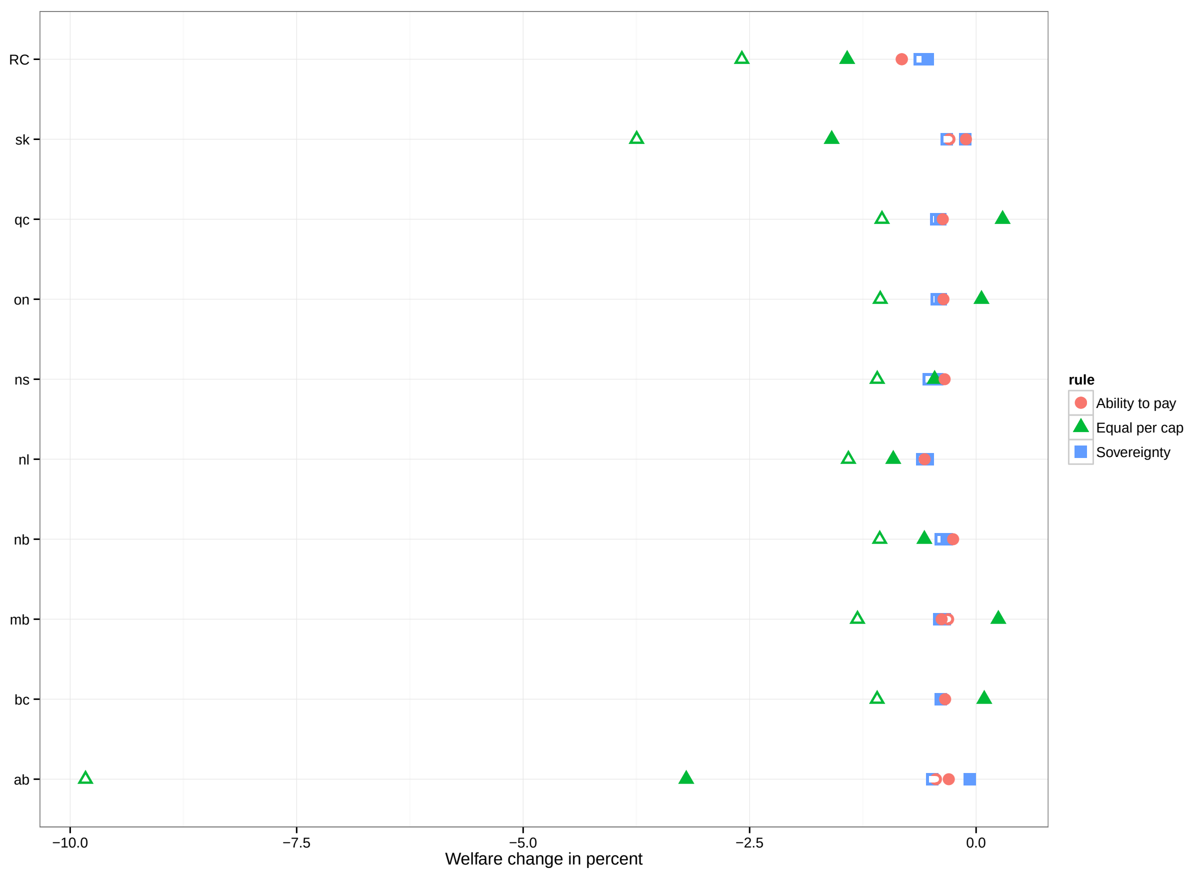


Figure 5: Hicksian equivalent variation in income under alternative burden sharing rules. Model runs with no permit trading permitted between regions are represented by hollow symbols, and those with permit trading between regions are represented with solid symbols.

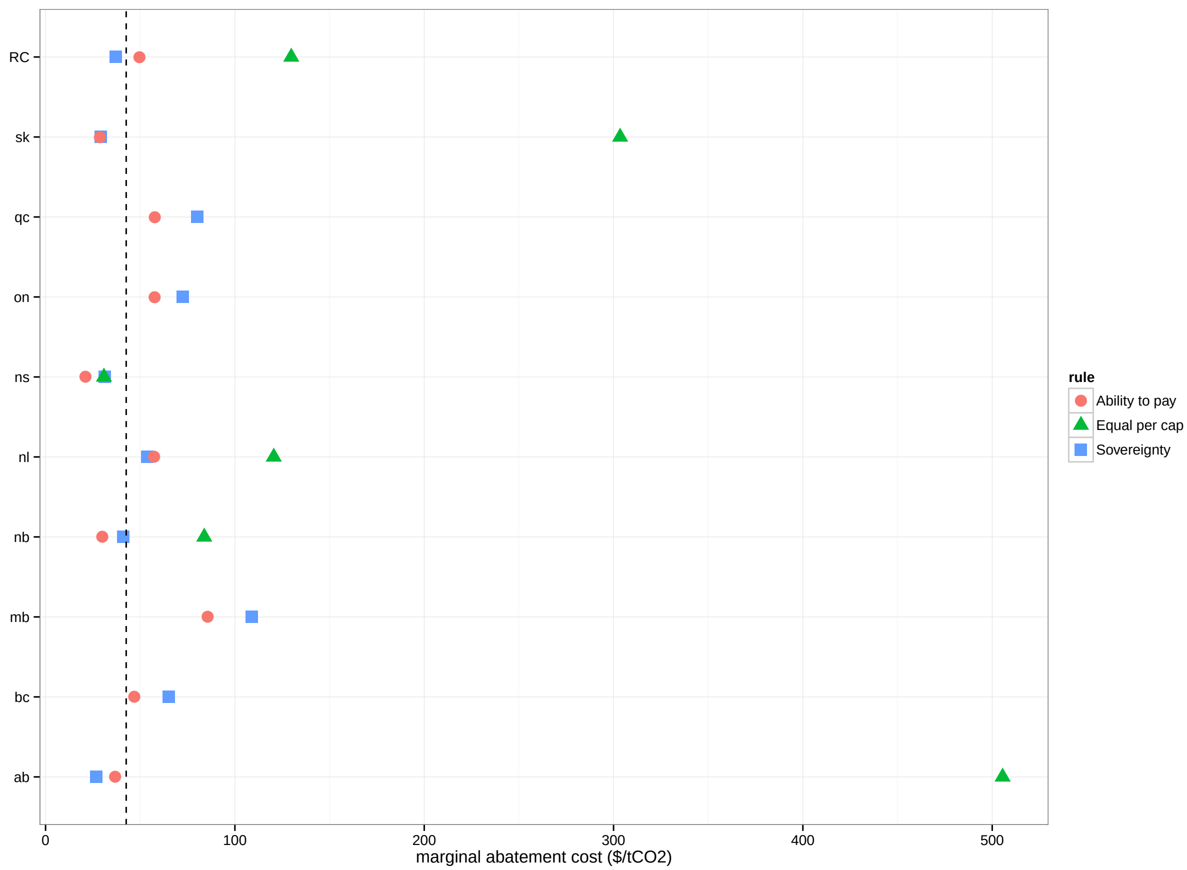


Figure 6: Equilibrium emission permit prices under alternative burden sharing rules for runs. Model runs with no permit trading are given as symbols, while model runs with permit trading are shown with the dashed line (prices are (nearly) invariant to burden sharing rule in this case).

# C Algebraic model summary (not for publication)

The model is formulated as a system of nonlinear inequalities. The inequalities correspond to the three classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers, (ii) market clearance for all goods and factors and (iii) income-expenditure balances. The first class determines activity levels, the second class determines prices and the third class determines incomes. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition and an income to an income-expenditure balance.[28] Constraints on decision variables such as prices or activity levels allow for the representation of market failures and regulation measures. These constraints go along with specific complementary variables. In the case of price constraints, a rationing variable applies as soon as the price constraint becomes binding; in the case of quantity constraints, an endogenous tax or subsidy is introduced.[29]

In our algebraic exposition of equilibrium conditions below, we state the associated equilibrium variables in brackets. Furthermore, we use the notation $\Pi_{gr}^{Z}$ to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale production of item $g$ in region $r$ where $Z$ is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's Lemma), which appear subsequently in the market clearance conditions.

We use $g$ as an index comprising all sectors/commodities including the final consumption composite, the public good composite and an aggregate investment good. The index $r$ (aliased with $s$) denotes regions. The index $EG$ represents the subset of all energy goods except for crude oil (here: coal, refined oil, gas, electricity) and the label $X$ denotes the subset of fossil fuels (here: coal, crude oil, gas), whose production is subject to decreasing returns to scale given the fixed supply of

[28]Due to non-satiation expenditure will exhaust income. Thus, the formal inequality of the income-expenditure balance will hold as an equality in equilibrium.

[29]An example for an explicit price constraint is a lower bound on the real wage to reflect a minimum wage rate; an example for an explicit quantity constraint is the specification of a (minimum)target level for the provision of public goods.

fuel-specific factors. Tables 10 to 17 explain the notations for variables and parameters employed within our algebraic exposition. Figures 2 to 4 provide a graphical representation of the functional forms. Numerically, the model is implemented under GAMS (Brooke et al. 1996)[30] and solved using PATH (Dirkse and Ferris 1995)[31].

*Zero profit conditions*

1. Production of goods except for fossil fuels ($Y_{gr}|_{g \notin X}$):

$$\begin{aligned}\Pi_{gr}^{Y} = & \left(\theta_{gr}^{EX}\left(\frac{P_{gr}^{Y}(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{P}_{gr}^{Y}}\right)^{1+\eta} + \left(1-\theta_{gr}^{EX}\right)\left(\frac{\mu(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{\mu}_{gr}}\right)^{1+\eta}\right)^{\frac{1}{1+\eta}} \\ & - \left(\theta_{gr}^{M}{P_{gr}^{M}}^{1-\sigma^{M}} + (1-\theta_{gr}^{M})\left(\left(\left(\theta_{gr}^{E}{P_{gr}^{E}}^{1-\sigma^{E}} + (1-\theta_{gr}^{E})\left(\theta_{gr}^{L}{P_{r}^{L}}^{1-\sigma^{L}} + (1-\theta_{gr}^{L}){P_{gr}^{K}}^{1-\sigma^{L}}\right)^{\frac{1}{1-\sigma^{L}}}\right)^{1-\sigma^{E}}\right)^{\frac{1}{1-\sigma^{E}}}\right)^{1-\sigma^{M}}\right)^{\frac{1}{1-\sigma^{M}}} \\ & \leq 0\end{aligned}$$

2. Production of fossil fuels ($Y_{gr}|_{g \in X}$):

$$\begin{aligned}\Pi_{gr}^{Y} = & \left(\theta_{gr}^{X}\left(\frac{P_{gr}^{Y}(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{P}_{gr}^{Y}}\right)^{1+\eta} + \left(1-\theta_{gr}^{X}\right)\left(\frac{\mu(1-tp_{gr}^{Y}-tf_{gr}^{Y})}{\bar{\mu}_{gr}}\right)^{1+\eta}\right)^{\frac{1}{1+\eta}} \\ & - \left(\theta_{gr}^{R}\left(\frac{P_{gr}^{R}(1+tp_{gr}^{R}+tf_{gr}^{R})}{\bar{P}_{gr}^{R}}\right)^{1-\sigma_{gr}^{R}} + \left(1-\theta_{gr}^{R}\right)\left(\theta_{gr}^{L}P_{r}^{L} + \sum_{i}\theta_{igr}^{R}\frac{(P_{ir}^{A}(1+tp_{igr}^{D}+tf_{igr}^{D}) + a_{igr}^{CO_2}P^{CO_2})}{\bar{P}_{igr}^{A}}\right)^{1-\sigma_{gr}^{R}}\right)^{\frac{1}{1-\sigma_{gr}^{R}}} \\ & \leq 0\end{aligned}$$

3. Sector-specific material aggregate ($M_{gr}$):

$$\Pi_{gr}^{M} = P_{gr}^{M} - \left(\sum_{i \notin EG}\theta_{igr}^{M}\left(\frac{P_{ir}^{A}(1+tp_{igr}^{D}+tf_{igr}^{D})}{\bar{P}_{igr}^{A}}\right)^{1-\sigma^{D}}\right)^{\frac{1}{1-\sigma^{D}}} \leq 0$$

[30] Brooke, A., D. Kendrick and A. Meeraus (1996), *GAMS: A User's Guide*, Washington DC: GAMS

[31] Dirkse, S. and M. Ferris (1995), "The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems", *Optimization Methods & Software 5*, 123-156.

4. Sector-specific energy aggregate ($E_{gr}$):

$$\Pi^E_{gr} = P^E_{gr} - \Bigg(\Bigg(\theta_{ELEgr}\left(\frac{P^A_{ELEr}(1+tp^D_{ELEgr}+tf^D_{ELEgr})}{\bar{P}_{ELEgr}}\right)^{1-\sigma^{ELE}}$$
$$+(1-\theta_{ELEgr})\Bigg(\Bigg(\theta_{COAgr}\left(\frac{P^A_{COAr}(1+tp^D_{COAgr}+tf^D_{COAgr})}{\bar{P}_{COAgr}}+a^{CO_2}_{COAgr}P^{CO_2}\right)^{1-\sigma^{COA}}$$
$$+(1-\theta_{COAgr})\Bigg(\theta_{OILgr}\left(\frac{P^A_{OILr}(1+tp^D_{OILgr}+tf^D_{OILgr})}{\bar{P}_{OILgr}}+a^{CO_2}_{OILgr}P^{CO_2}\right)^{1-\sigma^{OIL}}$$
$$+\quad(1-\theta_{OILgr})\left(\frac{P^A_{GASr}(1+tp^D_{GASgr}+tf^D_{GASgr})}{\bar{P}_{GASgr}}+a^{CO_2}_{GASgr}P^{CO_2}\right)^{1-\sigma^{OIL}}\Bigg)^{\frac{1}{1-\sigma^{OIL}}}\Bigg)^{1-\sigma^{COA}}\Bigg)^{\frac{1}{1-\sigma^{COA}}}\Bigg)^{1-\sigma^{ELE}}\Bigg)^{\frac{1}{1-\sigma^{ELE}}}$$
$$\leq 0$$

5. Armington aggregate ($A_{ir}$):

$$\Pi^A_{ir} = P^A_{ir} - \left(\left(\Theta^{DM}_{ir}\mu^{1-\sigma^{DM}} + \left(1-\Theta^{DM}_{ir}\right)\left(\sum_s \Theta^{MM}_{isr} {P^Y_{is}}^{1-\sigma^{MM}_i}\right)^{\frac{1}{1-\sigma^{MM}}}\right)^{1-\sigma^{DM}}\right)^{\frac{1}{1-\sigma^{DM}}} \leq 0$$

6. Labor supply ($L_r$):

$$\Pi^L_r = \frac{P^L_r\left(1-tp^L_r-tf^L_r\right)}{\overline{P^L_r}} - P^{LS}_r \leq 0$$

7. Mobile capital supply ($K$):

$$\Pi^K = \left(\sum_r \Theta^K_r\left(\frac{P^K\left(1-tp^K_r-tf^K_r\right)}{\overline{P^K_r}}\right)^{1+\epsilon}\right)^{\frac{1}{1+\epsilon}} - P^{KM} \leq 0$$

8. Welfare ($W_r$):

$$\Pi^W_r = \left(\Theta^{LS}_r {P^{LS}_r}^{1-\sigma^{LS}_r} + \left(1-\Theta^{LS}_r\right){P^Y_r}^{1-\sigma^{LS}_r}\right)^{\frac{1}{1-\sigma^{LS}_r}} \leq 0$$

*Market clearance conditions*

9. Labor ($P^L_r$):

$$L_r \geq \sum_g Y_{gr}\frac{\partial \Pi^Y_{gr}}{\partial P^L_r}$$

10. Leisure ($P_r^{LS}$):

$$\overline{L}_r - L_r \geq W_r \frac{\partial \Pi_r^W}{\partial P^{LS}}$$

11. Mobile capital ($P^{KM}$):

$$\sum_r \overline{KM}_r \geq K$$

12. Sector-specific capital ($P_{gr}^K$):

$$\overline{K}_{gr} + K \frac{\partial \Pi^K}{\partial P_{gr}^K} \geq \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial P_{gr}^K}$$

13. Fossil fuel resources ($P_{gr}^R|_{g \in X}$):

$$\overline{R}_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial (P_{gr}^R (1 + tp_{gr}^R + tf_{gr}^R))}$$

14. Energy composite ($P_{gr}^E$):

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial P_{gr}^E}$$

15. Material composite ($P_{gr}^M$):

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial P_{gr}^M}$$

16. Armington good ($P_{ir}^A$):

$$A_{ir} \geq \sum_g E_{gr} \frac{\partial \Pi_{gr}^E}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D) + a_{igr}^{CO_2} P^{CO_2})} + \sum_g M_{gr} \frac{\partial \Pi_{gr}^M}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D))}$$

17. Commodities ($P_{ir}^Y$):

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial (p_{ir}^Y (1 - tp_{ir}^Y - tf_{ir}^Y))} \geq A_{ir} \frac{\partial \Pi_{ir}^A}{\partial P_{ir}^Y}$$

18. Private good consumption ($P^Y_{Cr}$):

$$Y_{Cr} \geq W_r \frac{\partial \Pi^W_r}{\partial P^Y_{Cr}}$$

19. Investment ($P^Y_{Ir}$):

$$Y_{Ir} \geq \bar{I}_r$$

20. Public Consumption ($P^Y_{Gr}$):

$$Y_{Gr} \geq \frac{INC^p_r}{P^Y_{Gr}} + \theta^G_r \frac{INC^f}{P^Y_{Gr}}$$

21. Welfare ($P^W_r$):

$$W_r \geq \frac{INC^{RA}}{P^W_r}$$

22. Carbon emissions ($P^{CO}_2$):

$$\overline{CO_2} \geq \sum_r \sum_{i \in EG} \sum_g E_{gr} \frac{\partial \Pi^E_{gr}}{\partial (P^A_{ir}(1 + tp^D_{igr} + tf^D_{igr}) + a^{CO_2}_{igr} P^{CO_2})}$$

*Income-expenditure balances*

23. Income of representative consumer ($INC^{RA}_r$):

$$\begin{aligned}
INC^{RA}_r = {} & P^{LS}_r \overline{L}_r \\
& + \sum_{x \in g} P^R_{gr} \bar{R}_{gr} \\
& + P^{KM} \overline{KM}_r \\
& + \sum_g P^K_{gr} \overline{K}_{gr} \\
& - P^Y_{Ir} \bar{I}_r \\
& + P^{CO_2} \theta^{CO_2}_r \overline{CO}_2 \\
& + \mu \overline{BOP}^{RA}_r \\
& - \chi_r \mu \\
& - \varepsilon_r P^Y_{Cr}
\end{aligned}$$

24. Income of provincial government ($INC_r^p$):

$$
\begin{aligned}
INC_r^p = & \, L_r \, P_r^L \, tp_r^L \\
& + \sum_{g \in x} \bar{R}_{gr} \, P_{gr}^R \, tp_{gr}^R \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial P_{gr}^K} \, P_{gr}^K \, tp_r^K \\
& + \sum_i \sum_g \Bigg( E_{gr} \frac{\partial \Pi_{gr}^E}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D) + a_{igr}^{CO_2} \, P^{CO_2})} \, P_{ir}^A \, tp_{igr}^D \\
& \qquad + \, M_{gr} \frac{\partial \Pi_{gr}^M}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D))} \, P_{ir}^A \, tp_{igr}^D \Bigg) \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial (p_{gr}^Y (1 - tp_{gr}^Y - tf_{gr}^Y))} \, P_{gr}^Y tp_{gr}^Y \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial (\mu (1 - tp_{gr}^Y - tf_{gr}^Y))} \, \mu tp_{gr}^Y \\
& + \mu \overline{BOP}_r^p \\
& + \chi_r \mu
\end{aligned}
$$

25. Income of federal government ($INC^f$):

$$
\begin{aligned}
INC^f = & \sum_r \Big( L_r \, P_r^L \, tf_r^L \\
& + \sum_{g \in x} \bar{R}_{gr} \, P_{gr}^R \, tf_{gr}^R \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial P_{gr}^K} \, P_{gr}^K \, tf_r^K \\
& + \sum_i \sum_g \Bigg( E_{gr} \frac{\partial \Pi_{gr}^E}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D) + a_{igr}^{CO_2} \, P^{CO_2})} \, P_{ir}^A \, tf_{igr}^D \\
& \qquad + \, M_{gr} \frac{\partial \Pi_{gr}^M}{\partial (P_{ir}^A (1 + tp_{igr}^D + tf_{igr}^D))} \, P_{ir}^A \, tf_{igr}^D \Bigg) \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial (p_{gr}^Y (1 - tp_{gr}^Y - tf_{gr}^Y))} \, P_{gr}^Y tf_{gr}^Y \\
& + \sum_g Y_{gr} \frac{\partial \Pi_{gr}^Y}{\partial (\mu (1 - tp_{gr}^Y - tf_{gr}^Y))} \, \mu tf_{gr}^Y \\
& + \mu \overline{BOP}^f \\
& + \, \varepsilon_r \, P_{cr}^Y \Big)
\end{aligned}
$$

26. Equal-yield for provincial government demand ($\chi_r$):

$$
\frac{INC_r^P}{P_{Gr}^Y} \geq \bar{G}_r^P
$$

27. Equal-yield for federal government demand ($\varepsilon$):

$$
\sum_r \theta_r^G \frac{INC^f}{P_{Gr}^Y} \geq \sum_r \bar{G}_r^f
$$

| Symbol | Description |
|---|---|
| $i$ | Goods excluding final demand goods |
| $g$ | Goods including intermediate goods ($g = i$) and final demand goods, i.e. private consumption ($g = C$), investment ($g = I$) and public consumption ($g = G$) |
| $r$ (alias $s$) | Regions |
| $EG$ | Energy goods: coal, refined oil, gas and electricity |
| $X$ | Fossil fuels: coal, crude oil and gas |

Table 10: Sets

| Symbol | Description |
|---|---|
| $Y_{gr}$ | Production of good $g$ in region $r$ |
| $E_{gr}$ | Production of energy composite for good $g$ in region $r$ |
| $M_{gr}$ | Production of material aggregate for good $g$ in region $r$ |
| $A_{ir}$ | Production of Armington good $i$ in region $r$ |
| $L_r$ | Labour supply in region $r$ |
| $K$ | Capital supply |
| $W_r$ | Production of composite welfare good |

Table 11: Activity variables

## C.1 Notation

| | |
|---|---|
| $p^Y_{gr}$ | Price of good $g$ in region $r$ |
| $p^E_{gr}$ | Price of energy composite for good $g$ in region $r$ |
| $p^M_{gr}$ | Price of material composite for good $g$ in region $r$ |
| $p^A_{ir}$ | Price of Armington good $i$ in region $r$ |
| $p^L_r$ | Price of labour (wage rate) in region $r$ |
| $p^{LS}_r$ | Price of leisure in region $r$ |
| $P^K_{gr}$ | Price of capital services (rental rate) in sector $g$ and region $r$ |
| $p^R_{gr}$ | Rent to fossil fuel resources in fuel production in sector $g$ ($g \in X$)and region $r$ |
| $p^{CO_2}$ | $CO_2$ price |
| $p^{KM}$ | Price of interregionally mobile capital |
| $p^K_{gr}$ | Price of sector-sector specific capital |
| $p^W_r$ | Price of composite welfare (utility) good |
| $\mu$ | Exchange rate |

Table 12: Price variables

| Symbol | Description |
|---|---|
| $INC^{RA}_r$ | Income of representative agent in region $r$ |
| $INC^p_r$ | Income of provincial government in region $r$ |
| $INC^f$ | Income of federal government |

Table 13: Income Variables

| Symbol | Description |
|---|---|
| $tp^Y_{gr}$ | Provincial taxes on output in sector $g$ and region r |
| $tf^Y_{gr}$ | Federal taxes on output in sector $g$ and region $r$ |
| $tp^R_{gr}$ | Provincial taxes on resource extraction in sector $g$ and region $r$ |
| $tf^R_{gr}$ | Federal taxes on resource extraction in sector $g$ and region $r$ |
| $tp^D_{igr}$ | Provincial taxes on intermediate good $i$ in sector $g$ and region$r$ |
| $tf^D_{igr}$ | Federal taxes on intermediate good $i$ in sector $g$ and region$r$ |
| $tp^L_r$ | Provincial taxes on labour in region $r$ |
| $tf^L_r$ | Federal taxes on labour in region $r$ |
| $tp^K_r$ | Provincial taxes on capital in region $r$ |
| $tf^K_r$ | Federal taxes on capital in region $r$ |
| $\bar{P}^Y_{gr}$ | Reference price of good $g$ in region $r$ |
| $\bar{\mu}_{gr}$ | Reference value of exchange rate |
| $\bar{P}^R_{gr}$ | Reference price of fossil fuel resource $g$ in region $r$ |
| $\bar{P}^A_{ir}$ | Reference price of Armington good $i$ in region $r$ |
| $\bar{P}^L_r$ | Reference price of labour (wage rate) in region $r$ |
| $\bar{P}^K_r$ | Reference price of capital in region $r$ |

Table 14: Tax rates and reference prices

| Symbol | Description |
|---|---|
| $\theta_{gr}^{EX}$ | Value share of international market exports in domestic production of good $g$ in region $r$ |
| $\theta_{gr}^{E}$ | Value share of energy in the production of good $g$ in region $r$ |
| $\theta_{gr}^{M}$ | Value share of the material aggregate within the composite of value-added and material in the production of good $g$ in region $r$ |
| $\theta_{gr}^{L}$ | Value share of labor in the value-added composite of good $g$ production in region $r$ |
| $\theta_{gr}^{R}$ | Value share of fossil fuel resource in fossil fuel production ($g \in X$) in region $r$ |
| $\theta_{gr}^{ELE}$ | Value share of electricity in the energy composite of good $g$ production in region $r$ |
| $\theta_{gr}^{COA}$ | Value share of coal in the coal-oil-gas composite of good $g$ production in region $r$ |
| $\theta_{gr}^{OIL}$ | Value share of oil in the oil-gas composite of good $g$ production in region $r$ |
| $\theta_{ir}^{DM}$ | Value share of domestically produced inputs to Armington production of good $g$ in region $r$ |
| $\theta_{isr}^{MM}$ | Value share of imports from region $s$ in the import composite of good $i$ to region $r$ |
| $\theta_{r}^{K}$ | Value share of capital supply to region $r$ in overall (mobile) capital supply |
| $\theta_{r}^{LS}$ | Value share of leisure demand in region $r$ |
| $\theta_{r}^{G}$ | Share of region $r$ in overall public good consumption |
| $\theta_{r}^{CO_2}$ | Share of region $r$ in overall $CO_2$ emission endowment |

Table 15: Cost shares

| Symbol | Description |
|---|---|
| $\overline{L}_r$ | Aggregate time (labor and leisure) endowment of region $r$ |
| $\overline{K}_{gr}$ | Sector-specific capital endowment of region $r$ |
| $\overline{R}_{gr}$ | Endowment of fossil fuel resource $g$ by region $r$ ($g \in X$) |
| $\overline{BOP}_r^{RA}$ | Representative agent's balance of payment deficit or surplus in region $r$ |
| $\overline{BOP}_r^{p}$ | Provincial government's balance of payment deficit or surplus in region $r$ |
| $\overline{BOP}^{f}$ | Federal government's initial balance of payment deficit or surplus |
| $\overline{CO_2}$ | Endowment with carbon emission rights |
| $a_{igr}^{CO_2}$ | Carbon emissions coefficient for fossil fuel $i$ ($i \in X$)in good $g$ production of region $r$ |
| $\overline{I}$ | Exogenous investment demand |
| $G_r^p$ | Exogenous provincial government demand |
| $G_r^f$ | Exogenous federal government demand |

Table 16: Endowments and emissions coefficients

| Symbol | Description |
|---|---|
| $\chi_r$ | Lump-sum transfers to warrant equal-yield constraint for provincial government $r$ |
| $\varepsilon_r$ | Lump-sum transfers to warrant equal-yield for federal government |

Table 17: Additional variables

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